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Performance of Renewable Energy Charging Stations for Electric Vehicles with Wireless Power Transfer

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Abstract

The shift towards sustainable energy solutions, particularly renewable energy sources and electric vehicles (EVs), has led to a need for efficient and convenient charging infrastructure. Traditional plug-in charging stations have limitations in accessibility, convenience, and user experience. Wireless power transfer (WPT) technology offers a promising alternative by enabling contactless energy transfer, enhancing user convenience and potentially increasing charging efficiency. This study investigates the performance of renewable energy charging stations for EVs integrated with WPT systems. These stations aim to reduce dependency on fossil fuels, lower greenhouse gas emissions, and contribute to a more sustainable transportation ecosystem. The integration of WPT technology further enhances the potential of these stations by providing seamless and efficient charging solutions for EV users. The research aims to evaluate the efficiency, reliability, and practicality of renewable energy-powered WPT charging stations. The results of the test show that the inductive method is more effective and has an impressive power transfer efficiency of 91.1%.

Keywords: *Electric vehicles; Wireless power transfer; Microgrid.*

Yenilenebilir Enerji ile Elektrikli Araçlar için Kablosuz Şarj İstasyonlarının Performansı

Özet

Sürdürülebilir enerji çözümlerine, özellikle yenilenebilir enerji kaynaklarına ve elektrikli araçlara (EV'ler) yönelik kayma, verimli ve kullanışlı şarj altyapısına olan ihtiyacı artırmaktadır. Geleneksel fişli şarj istasyonları, erişilebilirlik, kullanım kolaylığı ve kullanıcı deneyimi açısından sınırlamalara sahiptir. Kablosuz enerji transferi (WPT) teknolojisi, temassız enerji aktarımını mümkün kılarak kullanıcı konforunu artırmakta ve potansiyel olarak şarj verimliliğini artırmaktadır. Bu çalışma, WPT sistemleriyle entegre edilmiş yenilenebilir enerji şarj istasyonlarının performansını araştırmaktadır. Bu istasyonlar, fosil yakıtlara bağımlılığı azaltmayı, sera gazı emisyonlarını düşürmeyi ve daha sürdürülebilir bir ulaşım ekosistemine katkıda bulunmayı hedeflemektedir. WPT teknolojisinin entegrasyonu, EV kullanıcıları için kesintisiz ve verimli şarj çözümleri sağlayarak bu istasyonların potansiyelini daha da artırmaktadır. Araştırma, yenilenebilir enerjiyle çalışan WPT şarj istasyonlarının verimliliğini, güvenilirliğini ve pratikliğini değerlendirmeyi amaçlamaktadır. Test sonuçları, indüktif yöntemin daha etkili olduğunu ve etkileyici bir enerji transfer verimliliği olan %91.1'e sahip olduğunu göstermektedir.

Anahtar kelimeler: *Elektrikli araçlar; Kablosuz güç transferi; Mikro şebeke.*

1. Introduction

Over the past decade, the electric vehicle (EV) industry has undergone a huge change. The industry's production is growing from a micro standpoint to one that has global scale [1]. EVs have metamorphosed from just a niche product to the world's answer to reducing greenhouse gases and adapting climate change, by expanding their sphere of influence [2]. However, there are still many difficulties to be faced such as high infrastructure costs and inadequate charging stations, as well as 'fear of distance anxiety'h attery performance weakly [3]. Solutions could include extensive charging infrastructure, AI-enabled EVs and charging stations [4], and the introduction of Industry 4.0 [5]. Policy initiatives including financial subsidies and market price adjustments are likewise important [6]. Advances in battery technology are essential for overcoming these challenges [7]. Vehicles in the postal delivery system's last mile must navigate special challenges, such as fleet size and infrastructure [8]. A core issue is the insufficiency of EV charging infrastructure at present. In response, mobile charging stations (MCS) can provide flexible charging services [9]. Renewable energy sources, grid power supplies, and energy storage in Microgrids (MG) can all help to improve the reliability and stability of EV charging stations [10]. Big data can be used to model effective EV charging infrastructure [11]. Systematic energy management of MG charging stations can regulate power transfers [12, 13]. Ultrafast charging stations and power electronic topologies can further improve the efficiency of EV charging [14]. Charging strategies that are continuously differentiable with respect to current and based on models can cut charging times along with battery performance damage in DC MGs [15]. Nevertheless, there are still far too many areas with inadequate charging infrastructure for electric cars, to resort [16]. Accordingly, it is a significant change from the traditional mode of there being quite a bit of MG station for wireless charging to get rid of this problem.

Researches have explored wireless power transfer (WPT) for EVs, particularly in dynamic charging environments. Colombo et al. expect dynamic wireless charging will bring even greater convenience within reach when it comes to an EV's range [17]. Shanmugam et al. and Liu et al. address the technical aspects, touching on issues such as design parameters and control systems of dynamic wireless charging [18, 19]. Kumar et al. and Razu et al. stress practical benefits: smaller batteries, but fewer range anxieties [20, 21]. Subudhi and S provide a comprehensive overview of WPT topologies [22], while Zhang et al. discuss the potential of dynamic capacitive wireless charging for electric roadways [23]. Together, these studies show that WPT in general and dynamic charging specifically have the potential to transform the EV industry.

This study evaluates the performance of renewable energy-powered charging stations for electric vehicles (EVs) integrated with wireless power transfer (WPT) systems. By assessing the efficiency and reliability of these stations, the research aims to provide insights into their potential to reduce dependency on fossil fuels and lower greenhouse gas emissions. This evaluation is crucial in understanding how renewable energy can support the growing demand for EV charging infrastructure while promoting sustainable energy use.

A significant contribution of this study is its comparative analysis of capacitive and inductive wireless charging technologies for EVs. This analysis highlights the advantages and limitations of each technology, offering a comprehensive overview that can guide future improvements and developments in wireless charging systems. By understanding the strengths and weaknesses of these technologies, the study provides a foundation for optimizing EV charging methods.

The paper also delves into the energy conversion efficiency of renewable energy-powered WPT charging stations. It evaluates the contribution of these stations to a sustainable transportation ecosystem, exploring the long-term benefits and potential challenges associated with their deployment. This assessment underscores the importance of efficiency and sustainability in the design and implementation of EV charging infrastructure.

Finally, by bringing new ideas to environmental protection from a transportation perspective, this research aims to contribute to the development of environmentally friendly solutions for urban transportation. The study's findings support the goal of achieving harmonious urban development through sustainable and innovative technologies. By focusing on renewable energy and advanced charging systems, the research advocates for a greener and more sustainable future in urban mobility.

2. Methodology

The study employs a prototype microgrid (MG) station for electric vehicle (EV) wireless charging, designed using MATLAB. The prototype includes perfect components such as a hybrid photovoltaic (PV) system integrated with battery storage. The study evaluates the most commonly efficient types of wireless designs in EV charging. The prototype MG station was developed using MATLAB to simulate various scenarios and performance metrics. The design includes a hybrid photovoltaic (PV) system utilized for generating renewable energy and a battery storage system integrated to store excess energy and supply power during low solar irradiance. This setup ensures that the system can provide consistent power for EV charging, regardless of fluctuations in solar energy availability. The study focuses on evaluating different wireless charging designs for EVs, considering their efficiency and practicality. Among the designs assessed are Inductive Power Transfer (IPT), commonly used for its efficiency and robustness, and Capacitive Power Transfer (CPT). The performance of the wireless charging station was assessed based on energy transfer efficiency, system reliability. Energy transfer efficiency was measured to determine the effectiveness of the wireless charging system. System reliability was evaluated under different operating conditions to ensure consistent performance making it suitable for widespread use in urban and rural areas. Fig. 1 shows the scheme of study.

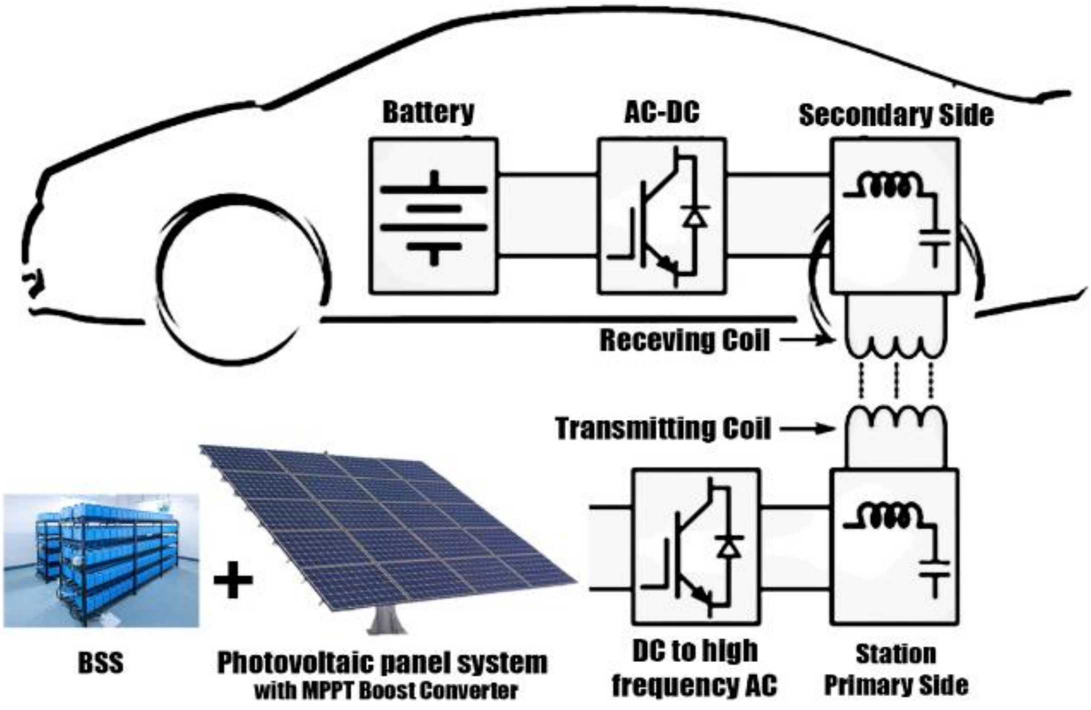

Figure 1. Scheme of proposed study

2.1. Primary side design

Solar electric power is the generation of electricity from sunlight. The A10 Green Technology's A10J-M60-230 monocrystalline PV module is used in generating electricity from sunlight. The A10J-M60-230 measures converts sunlight into electrical power using single crystal silicon cell. Polyester back sheet protects the module from the back with the feature of polyurethane. A10J-M60-230 monocrystalline PV module gives maximum power of 230 W of direct current and measures 0.01 noise coefficient. A10J-M60-230 together with any charge controller system can act as more resilient benefit due to the anodized aluminum frame. Table 1 depicts the A10J-M60-230 in detailed; it has high adaptability hence suitable for both commercial and industrial solar energy systems. Moreover, the module is simple, making it possible for several applications due to the less complex design.

Table 1. A10J-M60-230 solar panel parameters

Specification	**Value**
Maximum Power Output	230 W
Number of Cells per Module	60
Open Circuit Voltage	36.5 V
Short Circuit Current	8.3 A
Voltage at Maximum Power Point	29.4 V
Current at Maximum Power Point	7.82 A

The detailed system has 15 modules combined in parallel, while ten modules are in series. All the experiments were carried out with constant cell temperature as a base case in this study. The four main components of the DC-DC boost converter are a switching device, diode, inductor, and capacitor. The switching devices used in this simulation were a power Mosfet and a standard power diode based on the stable electrical function of low to moderate power. The method for operating the boost converter is the Maximum Power Point Tracking (MPPT) management algorithm, which is the P&O method. The dc-dc MPPT converter connected to high frequency dc-ac half bridge inverter.

2.2. Wireless power transfer technology

WPT is an innovative technology that can find its application in various spheres. It adopts an electromagnetic field that is spewed from a transmitter and then grasped by the receiver's antenna, where it is converted into electric power [24]. Despite the fact that the mathematical framework behind such technology is rather difficult, it remains to be imperative for the understanding of WPT. In addition to that, highly-efficient WPT systems can be developed for EV charging purposes, with a special focus on zero-voltage switching and variable angle phase shift control [25]. One of the most promising WPT types is Inductive Power Transfer, with a special comment on coil design, on working frequency choice, and on efficiency after implementation [26]. This effect is usually described by mutual inductance. In the given case, uptick in the current going through the primary coil makes the voltage induced in the secondary coil. This phenomenon can be demonstrated with the help of the e.g. (1) below.

$$V_2 = M\frac{dI_1}{dt} \tag{1}$$

where M represents mutual inductance and is a function of the geometric properties of the coils, the material properties of the two coils, and their location in space to each other. Thus, the primary coil induces the voltage due to varying current flowing through the secondary one, as shown in e.g. (2):

$$V_1 = M \frac{dI_2}{dt} \tag{2}$$

The voltage across each of the two inductively coupled coils can be described by e.g. (3) and (4).

$$V_1 = L_1 \frac{dI_1}{dt} + M \frac{dI_2}{dt} \tag{3}$$

$$V_2 = L_2 \frac{dI_2}{dt} + M \frac{dI_1}{dt} \tag{4}$$

The capacitance of primary and secondary side of a wireless transfer system can be calculated by e.g. (5).

$$Cp = Cs = \frac{1}{\omega^2 \cdot L_1} \tag{5}$$

The coefficient of coupling, denoted by k and provided in e.g. (6), quantifies the extent of magnetic linkage between two coils [26].

$$k = \frac{M}{\sqrt{L_1 L_2}} \tag{6}$$

The number of k being the proportional measure of the power transferred between the coils, this coefficient can range from zero, indicating uncoupled coils, to one, indicating completely coupled coils. The EV can get some energy from transmitting pad placed on the ground, with the primary coil L1. WPT transfer for EV is based on inductive coupling, which utilizes an oscillating magnetic field to achieve power transfer between two loops [27]. One coil is the transmitter, and it generates the magnetic field whereas the other coil captures energy being the receiver. The efficiency of the WPT transfer depends on the distance between the coils, their size, and frequency of alternating current. For the maximum power transfer efficiency, the two coils should be identical and close to each other as possible, residing in the same plane for which their frequency must be equal. In WPT systems of EVs, these coils can resemble flat loops, connected to the power supply and the battery [28].

2.2.1. Inductive wireless power charger

Inductive wireless power charging refers to a technology that applies electromagnetic induction for the transmission of power from a transmitting to a receiving unit without relying on physical connectors or cables. In this method, two coils are used; one is built into the transmitting unit, and the other is at the receiving end. The coil in the transmitter creates a magnetic field that extends to receptor unit's coil [29]. The magnetic force creates electric current in the receiver, which can be used to power the device or charge the battery. The wireless power charging approach is highly efficient when used over a short range. This means that the inductive method of charging powers all low to moderate power needs. This technology is suitable for several applications, such as charging EVs. The efficiency of inductive wireless power charging is highly dependent on the alignment of the transmitter and the receptor units' coils. When the two coils are highly aligned, there is optimal magnetic coupling, which makes it possible to successfully transmit the power from the transmitter to the receptor. When the coils are not properly aligned, magnetic coupling will be inferior. In this case, efficiency of energy transmission between the two ends will reduce, leading to prolonged time for battery charging and increased energy wastage [30].

One of the benefits of this kind of charging is that it does not require the application exterior connectors, which protects sensitive components. It applies magnet fields at frequencies safe for human beings. Nevertheless, considerable drawbacks are associated with the charging technology, particularly in terms of cost. To produce this technology, high-quality environmentally innocuous materials, such as copper coils and ferrite materials, are used. These materials are often costly. The initial adoption cost of inductive charging is higher compared to the standard wired counterparts that utilize inexpensive metals to produce. Figure 2 demonstrates the design of Inductive wireless power charging.

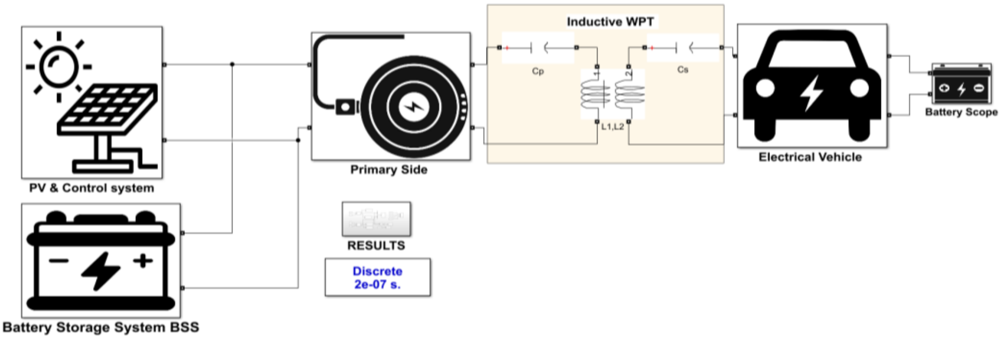

Figure 2. Simulink model of the proposed system based Inductive wireless power transfer

2.2.2. Capacitive power transfer charge

Figure 3 shows capacitive power transfer, where electric fields connect two metal plates that are used as capacitors. Even though this method can be efficient, its operation is more sensitive to environmental factors. It is not widely spread at the moment. A major advantage of such systems is that they are less sensitive to misalignment. However, implemented systems also have a smaller effective coupling area. Safety-wise, the developed devices are safe, but electric fields can interact with conductive materials in the operating environment, which introduces a challenge for further implementation [31]. This technology is early in development, and it can be used to charge portable devices or establish charging pads for EVs. The cost in comparison to inductive charging can be reduced due to lower costs of materials. However, the technology is immature, and further costs stem from the cost of development and implementation, as well as manufacturing at lower scales [32]. Overall, there are benefits and limitations to both inductive and capacitive chargers. The former is more widely used as of now since their technology is more developed, while the latter can offer the same level of operation for a lower cost. Selecting the one to use always depends on specific needs and limitations of practice.

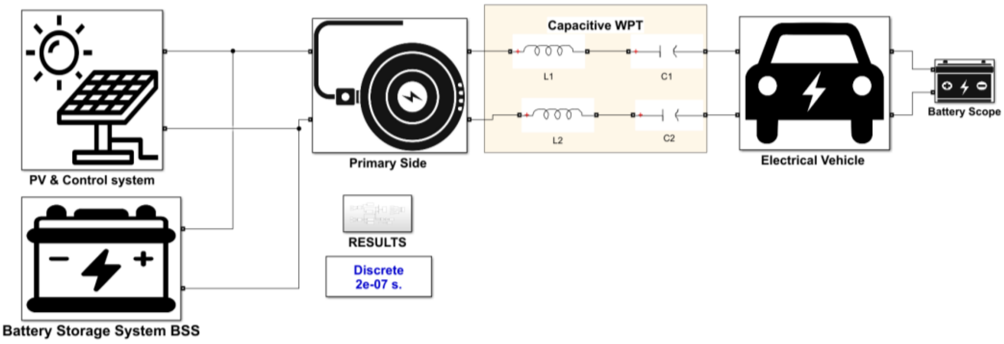

Figure 3. Simulink model of the proposed system based capacitive wireless power transfer

2.2.3. Enhancing WPT efficiency through resonance

The resonance phenomenon in WPT is a pivotal concept that amplifies the effectiveness and scope of energy delivery without needing wires. It's based on the principle of resonant inductive coupling, where two items are tuned to vibrate at an identical frequency, letting them interchange vigor more productively over a distance. Resonant inductive coupling involves two coils connected to their own capacitor: a sender and a recipient [33]. When powered by an alternating current, the transmitter emanates an oscillating magnetic field. If the acceptor coil is attuned to the identical resonant pitch as the transmitter, it can effectively seize the energy from the magnetic field, even if the coils aren't physically attached. The resonance effect considerably heightens the effectiveness and scope of wireless power conveyance, accomplishing high effectiveness even over distances several times the measurement of the coils. This is a considerable advancement over non-resonant inductive coupling, which necessitates the coils to be very close to [34].

3. Results and Discussion

This study introduces an effective low-cost MG capable of both PV systems and integrated battery energy storage. This system is in use to feed electric cars normally or both capacitive as well as inductive wireless power transfer feasible. Reduction of grid reliance is a fundamental feature for this set up using solar panels (Fig. 4).

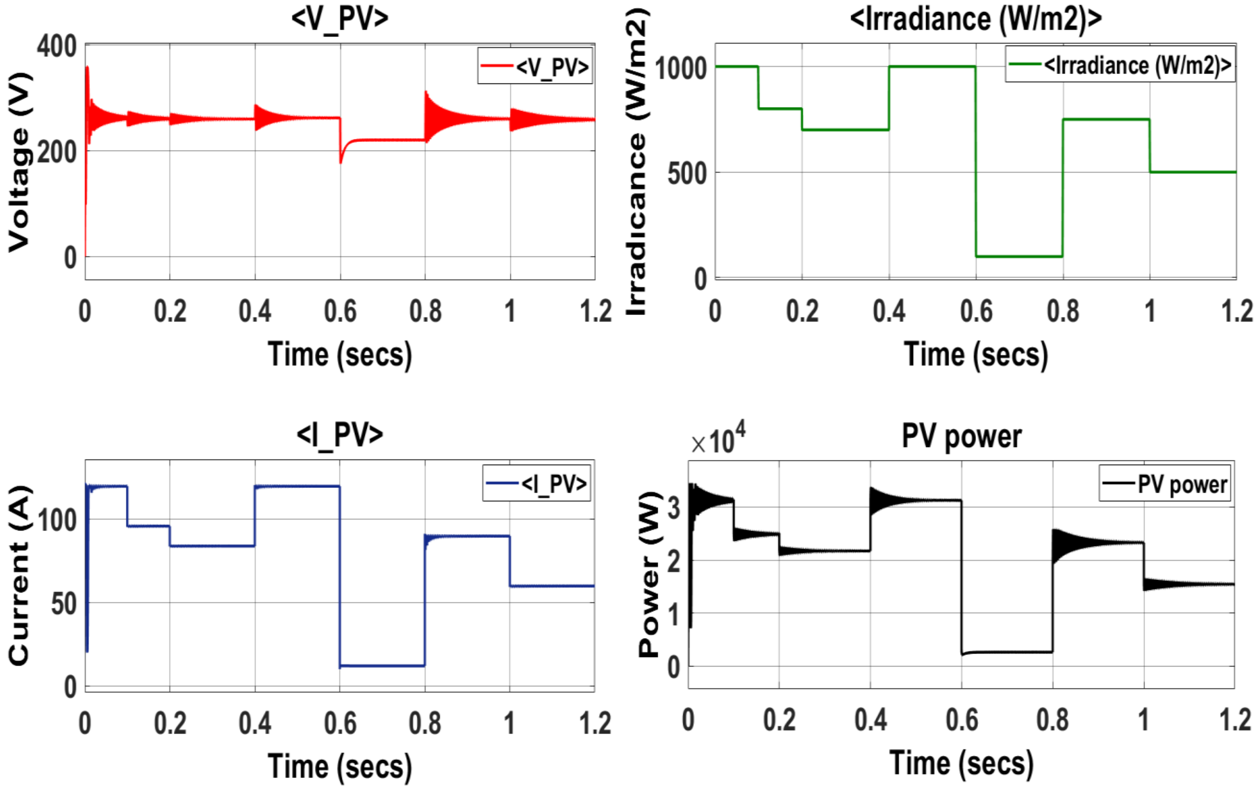

Figure 4. Performance of PV under different weather conditions

The operation of the PV system under different weather was evaluated. On an ideal day with clear skies and sunshine at full blast, the system can output up to 15 kW; At sunrise or sunset, however is when this upward trend starts to turn back down again—because even a single isolated cloud in front of your own eyes will cause everything becomes dim An MPPT DC-DC boost converter was necessary to ensure that the solar system's maximum energy collection was maintained, as shown in Fig. 5.

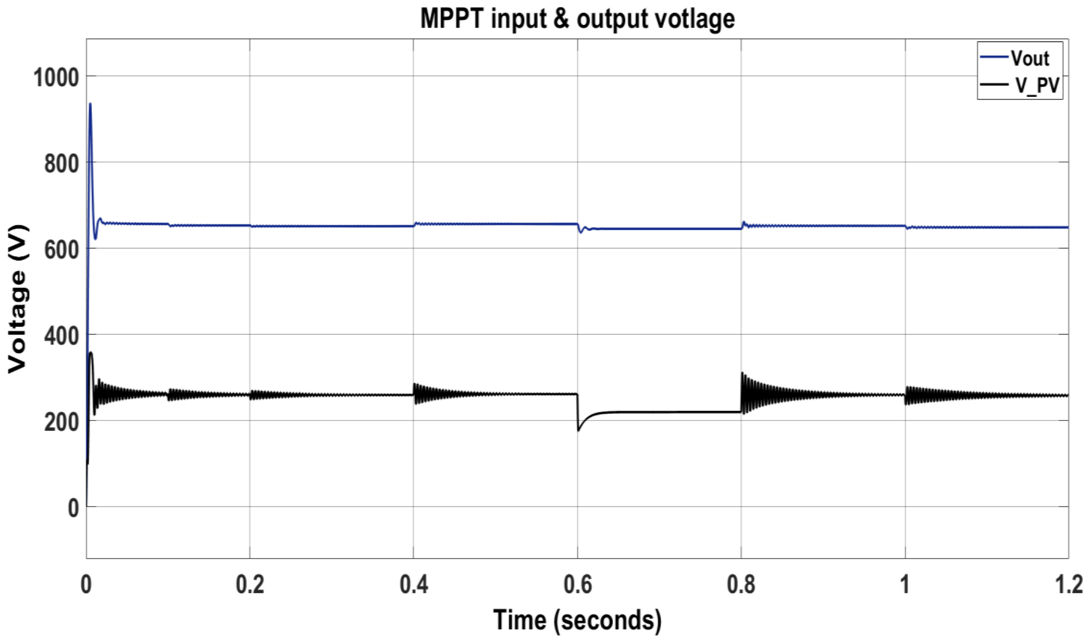

Figure 5. Input and output voltage based MPPT

During standard testing scenarios, the highest input voltage that the system, comprising PV sources and batteries, could handle was approximately 250 volts, while the maximum achievable output voltage was around 650 volts. The four primary components of a DC-DC boost converter include a switching device, a diode, an inductor, and a capacitor. In this simulation, the switching devices employed were a power Mosfet and a standard power diode, both commonly used in low- to medium-power applications. The functioning of the boost converter is governed by an algorithm known as MPPT, commonly referred to as P&O (Perturb and Observe). For this boost converter, specific components were selected: a capacitance of 4.5 mF and an inductance (L) of 0.5 mH. Fig. 6 illustrates the duty cycle of the P&O algorithm, which is integral to the MPPT boost converter's operation.

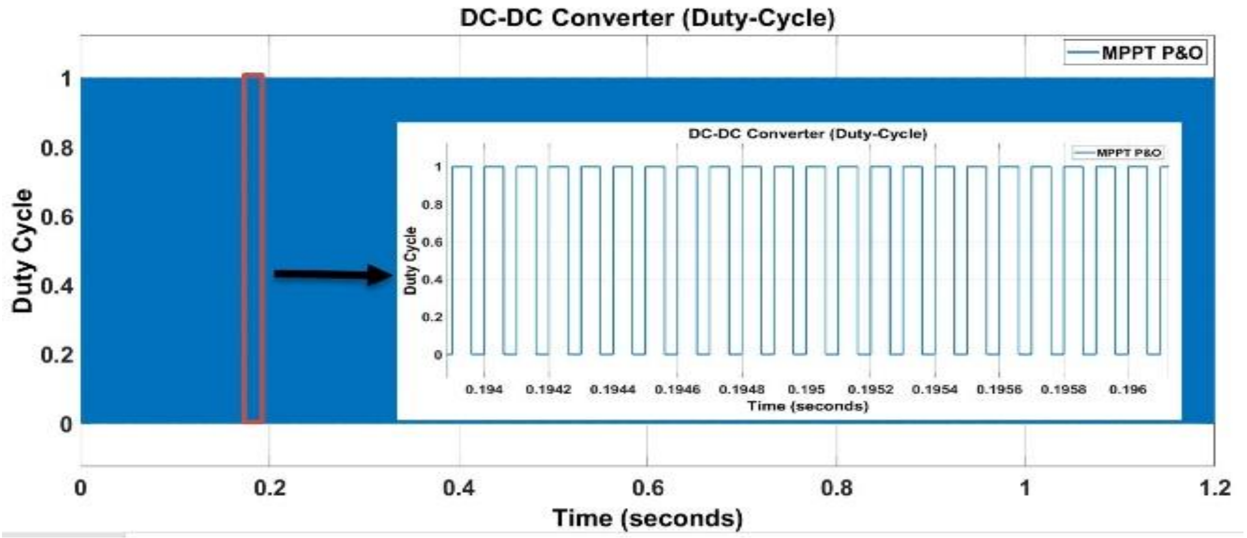

Figure 6. MPPT Duty cycle

Fig. 7 illustrates the performance of a battery storage system. Whether charging or discharging, the system operates with a 50-ampere output and a 650-volt output under highly diverse weather conditions. As Figure 6 indicates, the design of the booked-out battery storage system ensures that these processes do not have a considerable impact on the state of charge of the battery. The system is used to supply power to the EVs charging station, and the latter can work in cases when the corresponding PV system generates an insufficient amount of power. In addition, the reported system can change its operation to the charging mode in case of high or medium PV production when the demand for power also increases.

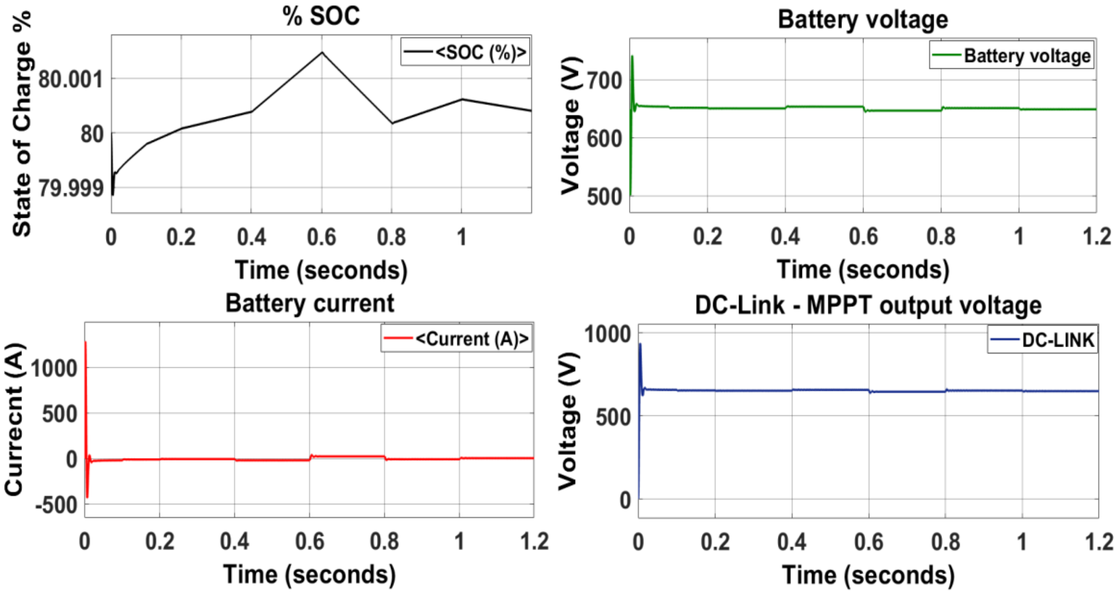

Figure 7. Performance of battery based different weather conditions

Fig. 8 indicates that by applying a high frequency rectifier which reached 50 kHz, we achieved wireless power transfer and created resonance conditions between current and voltage. The Current and Voltage approach a state of resonance. Such resonance energy efficiency occurs if the waves of current and voltage reach their peaks at the same time, which is known as 'phase alignment. 'Such synchronization is particularly important in wireless power transfer applications. This improves system performance significantly and energy efficiency to a great extent. This resonant state ensures that the system works properly and therefore must play an important regulatory role if we are to achieve. Equally it has the vital function of maximizing overall system efficiency.

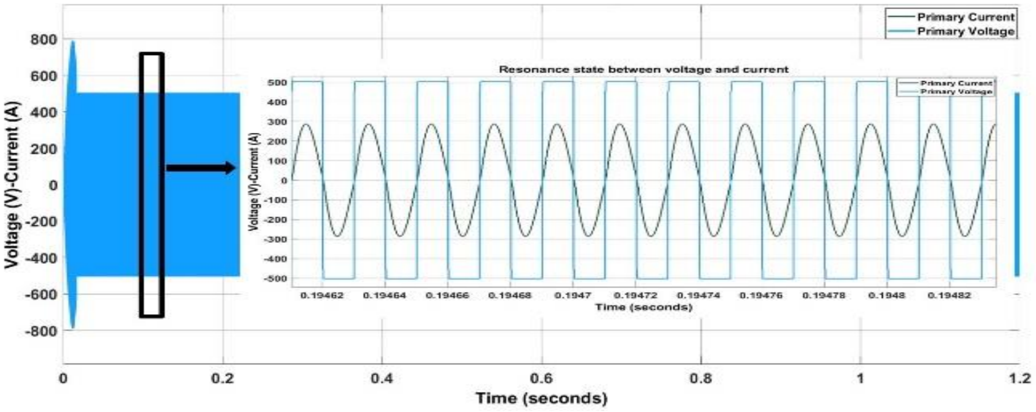

Figure 8. Current and voltage achieve a resonance state

In the test phase, the inductive wireless power charger achieved an average of 91.1% efficiency. A capacitive technology wireless power transfer system was also tested at the same time. It is noteworthy that as the spacing between two electrodes increases, so too does their efficiency remarkably, the system was able to maintain the stable power transmission as depicted in Fig. 8 and Fig. 9 across a gap as small as 100 mm.

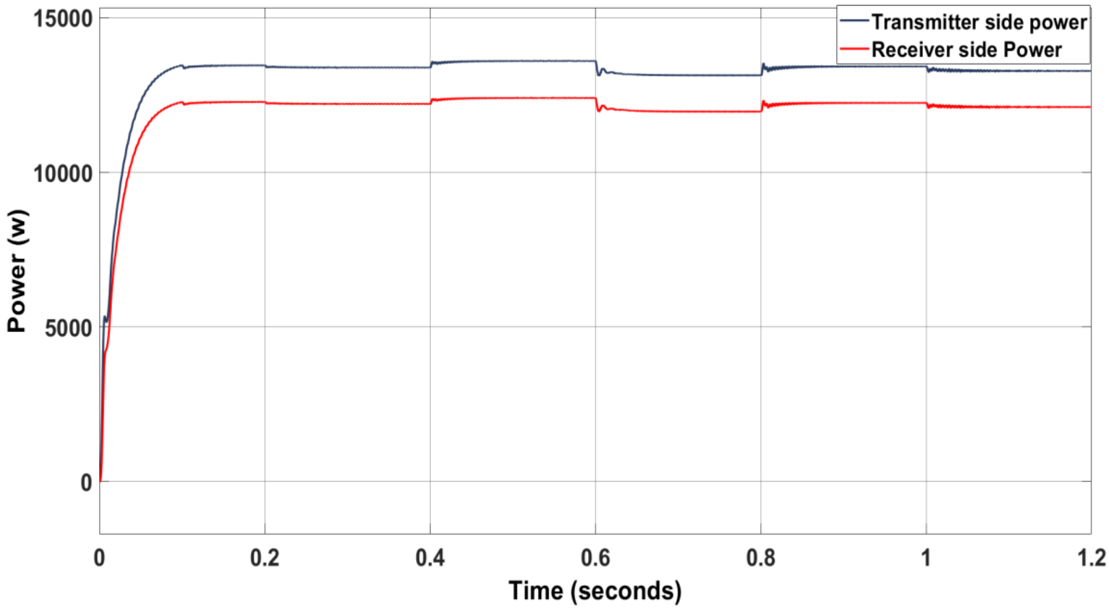

Figure 9. Inductive transmitter and receiver power side

In contrast, the capacitive power transfer charger exhibited an average efficiency of 89.72%. Fig. 10 illustrates the performance of the capacitive wireless transmission system under various weather conditions, with a specific focus on the transmitter and receiver sides.

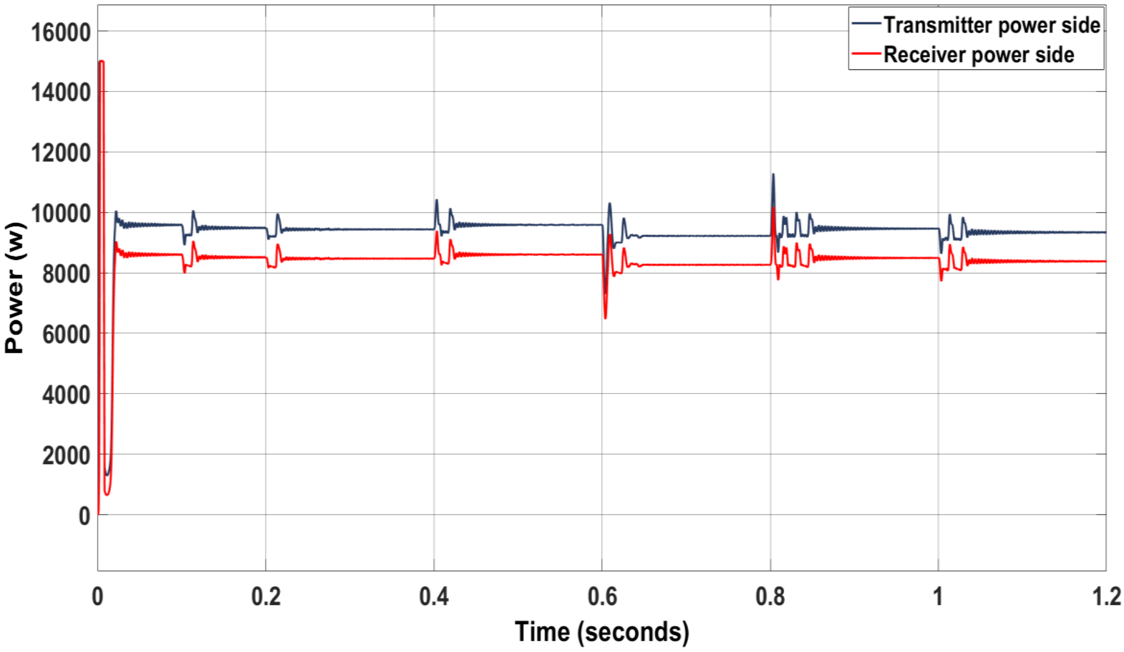

Figure 10. Capacitive transmitter and receiver power side

Table 2 shows the comparison between inductive and capacitive wireless

Table 2 Comparison between inductive and capacitive wireless

Type	**Transmitter power side** *(kW)*	**Receiver power side** (*kW)*	**Efficiency** (*%)*
Inductive	13.6 kW	12.37 kW	91.1
Capacitive	9.32 kW	8.36 kW	89.72

Inductive and capacitive wireless charging systems differ based upon their respective good and bad qualities: Although the inductive system is capable of achieving optimal efficiency, it requires very precise alignment, which is obtainable only by the use of expensive and complicated automatic alignment devices. In conditions where alignment can ordinarily be controlled, however, it may serve as the only economical choice to be used Contrarily, the capacitive system should maintain a definite distance although free of the influence from operational errors due to alignment instructions. The resulting situation is that in reality, vehicles may not always park at exactly the right distance and this fact is made more pronounced by worsened conditions.

Furthermore, from Fig. 9 and Fig.10, the system's reliability was further demonstrated through power transfer tests using inductive and capacitive methods. These tests highlighted the differences in performance and stability between the Inductive and Capacitive Power Transfer power transfer techniques. Inductive power transfer exhibits a quick rise in power and stabilizes around 12 kW on the transmitter side and 10 kW on the receiver side. The power remains stable with minimal fluctuations, indicating high reliability and consistent performance. This stability is crucial for applications where a steady power supply is essential, showcasing the effectiveness of inductive power transfer in maintaining reliable energy transmission. Capacitive power transfer, on the other hand, shows an initial quick rise in power but with more noticeable fluctuations. The power stabilizes around 10 kW on the transmitter side and 8 kW on the receiver side, with periodic fluctuations. Despite these fluctuations, the system maintains overall efficiency. However, the inductive power transfer appears to be more stable, suggesting that it might be the preferred method in scenarios where consistent power delivery is critical. The hybrid PV and battery storage system has demonstrated high reliability under various conditions. It maintains stable and efficient power transfer across different load conditions and solar irradiance levels. The comparison between inductive and capacitive power transfer methods further supports the robustness of the system, with inductive power transfer showing superior stability. These results confirm the system's ability to provide consistent and reliable performance, making it a dependable solution for various applications.

Table 2 shows the several studies comparison with proposed study

Table 3. Several studies comparison with proposed study

Authors	**Efficiency**	**Outcomes**
Mou et al., [35]	90%	Adaptive design to enhance energy efficiency, suitable for various EV models.
Rakouth et al., [36]	83%	Comprehensive analysis of efficiency optimization techniques and current technology trends.
Lu et al., [37]	74.1%	Focus on capacitive power transfer, high efficiency for stationary charging applications.
Throngnumchai et al., [38]	90%	Dynamic charging system with road-embedded coils, suitable for on-the-go EV charging.
Proposed Study	91.1%	Achieved high efficiency with the implemented wireless power transfer system.

In comparison, our study achieves a higher efficiency of 91%, which is notable compared to the other studies. This indicates an improvement in the wireless power transfer system's efficiency for electric vehicle charging applications.

4. Conclusion

This paper will take the solar powered micro grid stations as an example and explore whether they are viable for wirelessly recharging EVs. Its aim is to bring new ideas to environmental protection from a transportation aspect. Through a comparative analysis, this study analyses the application of capacitive wireless charging technology in EV charging against inductive wireless charging technology. Inductive charging technology, despite being sensitive to alignment, allows for a 91.1% efficiency when 13.6 kW is transmitted and 12.37 kW received. For future work, this paper proposes concrete improvements that could be made to solar powered MG stations for wirelessly charging EVs. It recommends that advanced alignment technology be developed to improve charging efficiency without adding any sophistication or cost to the system. There could be more study into control mechanisms for achieving distance with capacitive charging methodologies, using new sensors or even control algorithms If renewable energy sources, e.g. wind, hydroelectric power are combined with wireless charging systems then the carbon footprint of EV charging could be reduced and sustainable energy used to a much greater extent in the transportation sector. These changes will enable EVs to enjoy the full advantages of wireless technology and will con-Marie to the harmonious urban development goal ovid environmentally friendly solutions for transportation.

List of Symbols

EV	Electric vehicle
WPT	Wireless power transfer
MPPT	Maximum power point tracking
MG	Microgrid
PV	Photovoltaic
P&O	Perturb and Observe

Declarations and Ethical Standards

The author(s) declared no potential conflicts of interest with respect to the study, authorship, and/or publication of this article. The author(s) of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

Author Contribution

Abubaker Milad Abdalla SHABAAN conceived of the presented idea, methodology and findings. Fatih KORKMAZ supervised the findings of this study.

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